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Wave propagation in the 1999-2000 Arctic early winter stratosphere

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Abstract. Stratospheric wave propagation during the unusually cold NH early winter 99-00 is studied and compared to the recent cold winters of 94-95, 95-96 (the previous coldest NH winter) and 96-97. EP fluxes reveal less wave activity entered the stratosphere in 95-96 and 99-00, substantial temperature decreases during long periods of little wave activity in 94-95 and 99-00, and little wave propagation into the upper stratosphere in Nov 99-Jan 00 and Nov 95-mid-Jan 96. 2-D and 3-D EP fluxes for 95-96 and 99-00 show both that wave activity was inhibited from propagating upward and poleward through the middle stratosphere until mid-Jan, and there was large horizontal propagation of wave activity in the middle and lower stratosphere during Nov and Dec. Thus, both less wave activity entering the stratosphere, and a background structure that prevented wave activity from propagating into the upper stratosphere, were important factors in producing unusually cold early winters in 95-96 and 99-00.

Introduction and Approach

The 99-00 northern hemisphere (NH) early winter lower stratosphere was unusually cold, with minimum temperatures lower than any in the previous 8 years. Fig. 1 shows that The Met Office (UKMO) 46 hPa 99-00 early winter temperatures were lower than the previous coldest period in 95-96. A larger, more persistent area of stratospheric temperatures below the ~195 K polar stratospheric cloud (PSC) threshold was seen in Dec 99 and Jan 00 than previously observed [*Manney and Sabutis*, 2000, hereafter MS].

The 94-95, 95-96 and 96-97 NH winters were also usually cold (Fig. 1), with 2-2.5 month periods of temperatures continuously below PSC thresholds [*Pawson and Naujokat*, 1999]. 94-95 was unusually cold in Nov, Dec and early Jan; 95-96, the coldest overall NH winter on record, was unusually cold during Nov-Feb [e.g., *Naujokat and Pawson*, 1996]; 96-97 was unusually warm in Nov-Dec, but became unusually cold in Jan [*Coy et al.*, 1997]. In contrast, the 97-98 and 98-99 NH winters were both unusually warm [e.g., *Pawson and Naujokat*, 1999; *Manney et al.*, 1999].

Coy et al. [1997] and *Pawson and Naujokat* [1999] (and others) showed that 100 hPa eddy heat fluxes are lower during unusually cold NH winters. It is expected that both wave energy entering the stratosphere and characteristics of the background stratospheric flow play a role in determining stratospheric wave activity amplitude and propagation, and thus in the temperatures, since lower temperatures are associated with more quiescent stratospheric flows [e.g., *Murgatroyd and Singleton*, 1961]. In the following, wave activity and propagation are deduced from 2-D and 3-D Eliassen-Palm (EP) fluxes [e.g., *Andrews et al.*, 1987; *Plumb*, 1985] calculated from UKMO data for the 99-00 NH winter, and compared to the three cold winters mentioned above. We use 3-D EP fluxes [*Sabutis et al.*, 1997, and references therein] to detail the patterns and locations of wave propagation. 2-D and 3-D EP fluxes are calculated using wavenumbers 1-6 as described by *Sabutis* [1997] and *Sabutis et al.* [1997].

Results

Wave 1 dominated the Nov-mid-Jan spectrum during the years shown here; Fig. 2 shows time series of the vertical component of wave 1 EP flux at 100 hPa between Nov-Jan. The 100 hPa EP flux is often used as a measure of wave activity entering the stratosphere [e.g. *Coy et al.*, 1997; *Pawson and Naujokat*, 1999], and depends on the meridional eddy heat flux. Comparing Figs. 1 and 2, increases in temperature are correlated with periods of large positive ($> 0.8 \times 10^{12}$ kg m s^{-2}) EP flux; large wave activity in Dec-Jan 94-95 and 96-97 ($> 3.2 \times 10^{12}$ kg m s^{-2}) corresponds to times when temperatures are increasing to or above the 8-year average. Prolonged temperature decreases occur during periods of suppressed wave activity. Little wave activity ($< 0.8 \times 10^{12}$ kg m s^{-2}) in Nov-Dec 94 correlates with decreasing temperatures. 3-4 week periods of little vertical wave activity during Nov 99 and from mid-Dec 99 to mid-Jan 00 correlate with times when daily 46 hPa minimum temperatures decrease to their lowest values in the 9-year UKMO record.

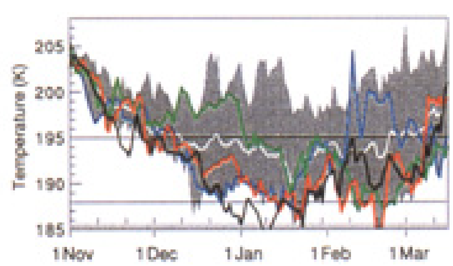

Figure 1. Minimum NH Nov-Mar UKMO temperatures north of 40°N at 46 hPa. Blue line shows 94-95, red 95-96, green 96-97 and black 99-00. Gray indicates the range of minimum temperatures during 91-92 through 98-99, and the white line shows the 8-year average.

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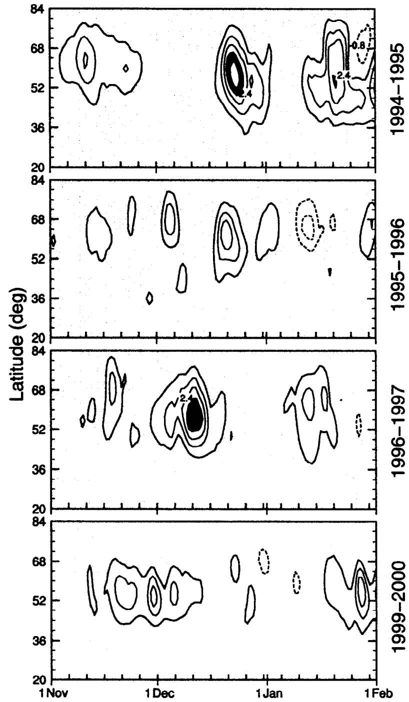

Figure 2. Vertical component of wave 1 EP Flux (10^{12} kg m s^{-2}) at 100 hPa for 94-95, 95-96, 96-97 and 99-00. Contour interval is 0.8, with light shading for values between -0.8 and 0.8, and dark shading between 3.2 and 4.0.

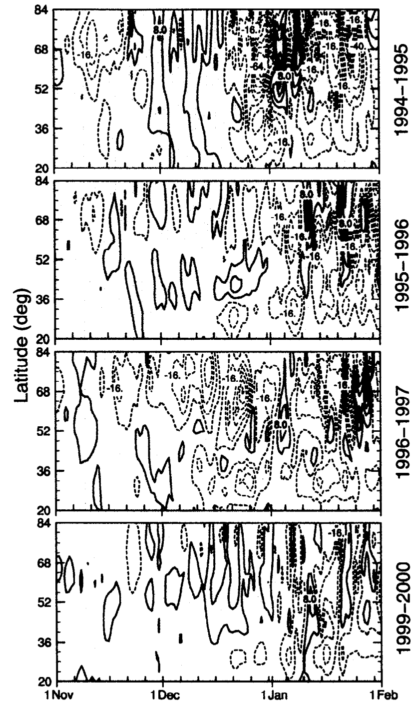

Figure 3. EP Flux divergence (m/s/d) at 2.2 hPa for Nov-Jan 94-95, 95-96, 96-97 and 99-00. Contour interval is 8, with values more positive than -8 shaded.

Overall, 95-96 had the least 100 hPa vertical wave activity, which may have played a role in producing unusually low temperatures. The lack of wave activity in Nov 99 allowed early winter temperatures to drop to unusually low values. The wave activity during early Dec 99 did not produce significant warming in the lower stratosphere, allowing 46 hPa temperatures to decrease to record minimums during the Dec 99-Jan 00 period with little wave activity. For recent warmer winters, prolonged periods (>3 weeks) with strong upward propagation were observed.

In an Eulerian approach, EP flux divergences are a measure of the zonal mean flow forcing by planetary waves [*Eliassen and Palm*, 1961]. In the upper stratosphere during 95-96 and 99-00 (Fig. 3), EP flux divergences were much smaller than in the other two years, with 99-00 values in Dec and early Jan slightly less than in 95-96. Also, the negative values in 95-96 and 99-00 do not extend as far poleward as those in 94-95 and 96-97. EP flux divergences at high latitudes are often associated with a zonal wind deceleration and residual circulation changes that warm the stratosphere. Analysis of an index of refraction for waves 1 and 2

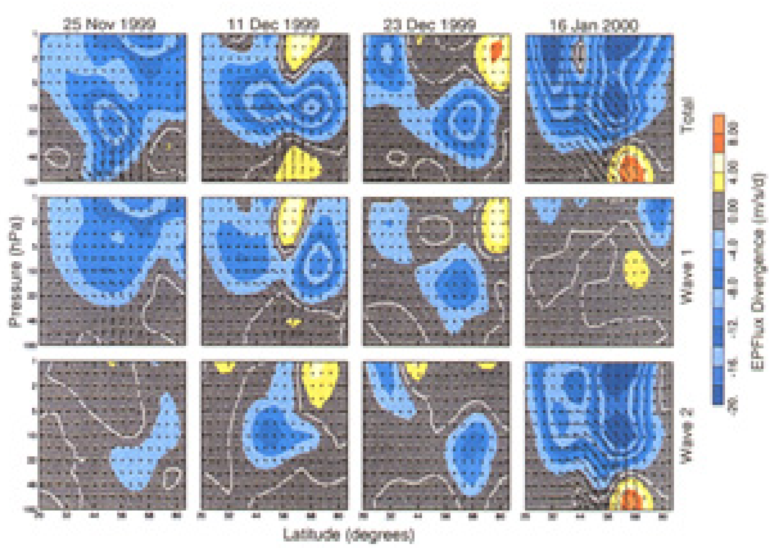

Figure 4. EP Flux vectors and divergence (m/s/d, colors) for selected days in the 99-00 NH early winter.

[*Matsuno*, 1970] also indicates that these waves were inhibited from propagating into the mid- and high-latitude upper stratosphere until early Jan in 96, and until mid-Jan in 2000. Lower stratospheric wave activity was consistent with upward propagation of wave activity shown in Fig. 2.

Fig. 4 shows EP fluxes and divergences on days in the 99-00 early winter during minor warming or wave amplification events [MS]. All show principally upward and equatorward wave propagation. Lack of zonal mean wind deceleration in the upper stratosphere is a factor in why low temperatures were observed during this period. The first three days show significant wave 1 EP flux divergence confined below ~10 hPa and equatorward of 70°N. On 11 and 23 Dec 99, wave 2 also propagates into the middle stratosphere and contributes to the wave forcing. The 16 Jan 00 field shows a wave 2 event, more typical of minor warmings in midwinter. By mid-Jan, wave activity could propagate into the upper stratosphere, and temperatures began to increase. Lower stratospheric temperatures were near average in early Feb, before again dropping to unusually low values [MS].

3-D EP fluxes provide additional information about wave propagation, by showing the longitude(s) where wave propagation is concentrated [e.g., *Sabutis et al.*, 1997]. Fig. 5 shows 3-D EP fluxes for three of the four days discussed above (11 Dec 99 patterns are similar to 25 Nov 99). During Nov and Dec, wave activity was concentrated over the Bering Sea, between 120° and 240°E. Vertical propagation was confined below ~5 hPa until mid-Jan, as noted above. A large amount of wave activity propagated horizontally poleward from late Nov through mid-Dec in the middle and lower stratosphere, but no significant wave activity was apparent in the upper stratosphere.

On 23 Dec 99, waves originating over the Bering Sea propagated upward and poleward to near 10 hPa, and then were reflected downward (broken contours) and equatorward near 300-330°E; thus, although there was substantial 3-D wave activity, the zonally averaged 2-D EP fluxes in Fig. 4 suggest little wave propagation. The presence of considerable wave activity is consistent with the asymmetry of the vortex seen at this time [MS]. Wave activity on 16 Jan 00 was dominated by wave 2 (see Fig. 4), and propagated vertically to above 2 hPa. Large wave-mean flow interactions in the upper stratosphere led to warming in that region. Consistent with the ability to propagate upward into the upper stratosphere, little wave activity was seen propagating horizontally at the lower levels.

Regions of upward (downward) 3-D EP fluxes are regions of downward (upward) air motion [e.g., *Sabutis et al.*, 1997]; downward (upward) air motion results in adiabatic heating (cooling). In the lower stratosphere on 25 Nov, 11 Dec (not shown) and 23 Dec 99, high temperature regions correspond to the locations of upward vertical 3-D EP flux. In addition, on 23 Dec 99, the cold pool was elongated to include the region of downward vertical EP flux. On 16 Jan 00, the cold region at 46 hPa was "pinched" by warmer regions at the locations of vertical wave activity, ~50° and 295°E.

Fig. 6 shows 3-D EP fluxes in late Dec 94, 95 and 96. Those on 20 Dec 95 are similar to Dec 99, whereas those in 94 and 96 show much more propagation into the upper stratosphere. As described above, wave activity for 20 Dec 95 is consistent with low temperatures being associated with little vertical wave propagation above 10 hPa. Higher early winter temperatures in 94-95 and 96-97 are associated with significant vertical wave activity propagating

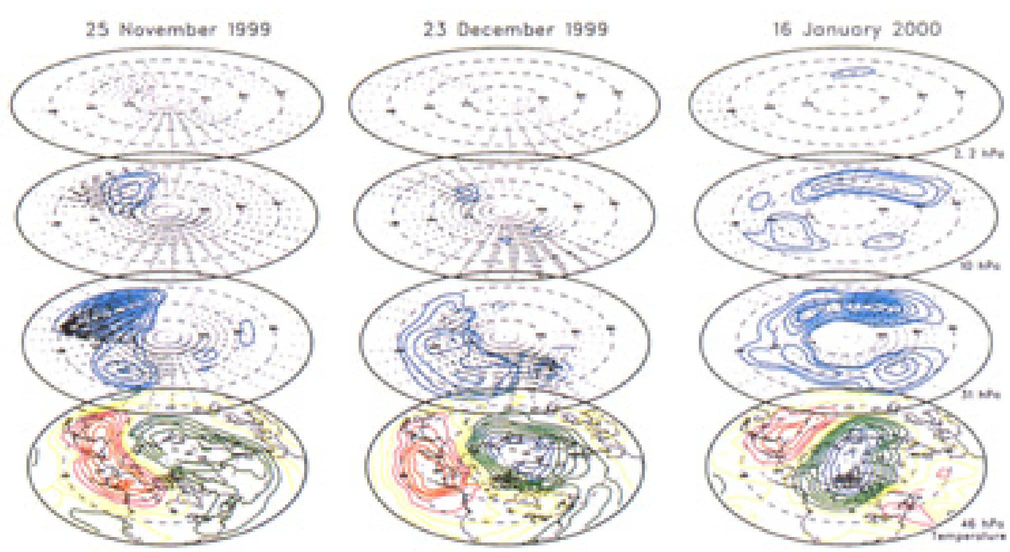

Figure 5. Top three levels: 3-D EP fluxes for days during the 99-00 early winter at 31, 10, and 2.2 hPa; cyan contours show the vertical component, and vectors the horizontal components; solid (dashed) cyan contours indicate upward (downward) energy propagation. Bottom level: 46 hPa temperatures; contour interval is 2.5 K, with blue contours up to 195 K, green 197.5 to 207.5 K, yellow 210 to 215 K, magenta 217.5 to 220 K, and red 222.5 K and above.

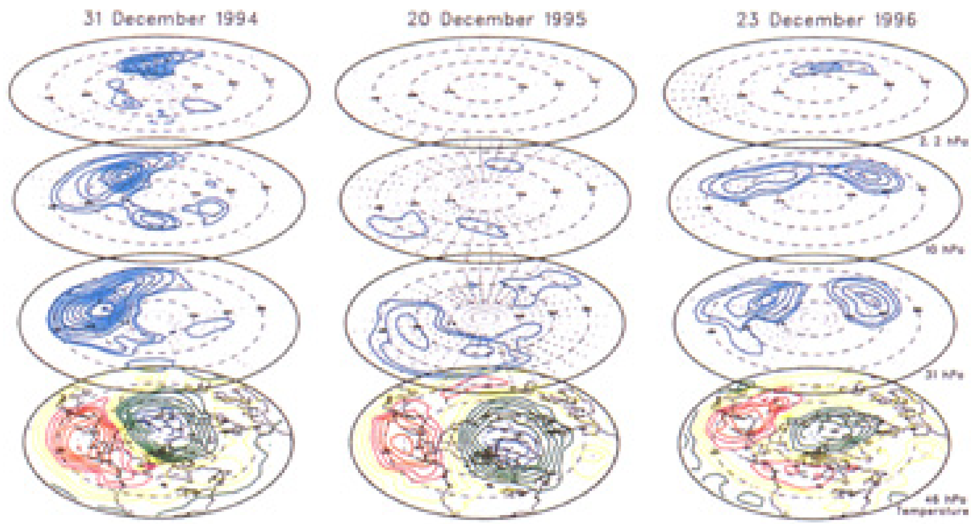

Figure 6. 3-D EP fluxes in late Dec 94, 95 and 96, at 31, 10, and 2.2 hPa. Layout is as in Fig. 5.

to 2 hPa. The 3-D EP fluxes show that even during a time of decreasing wave activity entering the stratosphere in late-Dec 94 and 96 (Fig. 2), substantial vertically propagating wave activity reaches the upper stratosphere and contributes to the warming trends seen in Fig. 1.

Summary and Conclusions

2-D and 3-D EP fluxes are used to study wave propagation during the unusually cold NH early winter 99-00, and are compared to other recent unusually cold winters. The EP fluxes show less wave activity entering the stratosphere in 95-96 and 99-00, with substantial temperature decreases during long periods (3-4 weeks) of reduced wave activity in 94-95 and 99-00. EP flux divergences indicate little wave propagation into the mid- and high-latitude upper stratosphere in Nov 99-Jan 00, and Nov 95-mid-Jan 96; this resulted in less deceleration of the jet and less accompanying change in the residual circulation, changes that would tend to warm the stratosphere. Detailed examination of 2-D and 3-D EP fluxes shows that wave activity was inhibited from propagating upward past the mid-stratosphere until mid-Jan in 96 and 2000; this was associated with large horizontal propagation of wave activity during Nov and Dec. Our analysis indicates that less wave activity entering the stratosphere, prolonged periods of little wave activity, and a background structure such that wave propagation into the mid- and high-latitude upper stratosphere was prevented, were important factors in producing the unusually cold early winters in 95-96 and 99-00.

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